DEVELOPMENT OF TEST PROCEDURES AND PERFORMANCE CRITERIA TO IMPROVE COMPATIBILITY IN CAR FRONTAL COLLISIONS

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ABSTRACT

Compatibility is now recognised as the next major step forward for improved car occupant secondary safety. The work reported here forms part of a research project that was undertaken to understand the current compatibility problems in car to car collisions and develop crash evaluation procedures that are suitable for consumer and legislative testing. The research performed to date has focused on the structural performance of vehicles in order to provide a safe environment for the protection of the occupants. This should also provide sufficient space to allow intelligent restraint systems of the future to operate effectively. This paper outlines the present understanding of compatibility for frontal impact collisions and reports the current state of development of three possible test procedures to address the fundamental issues, namely: structural interaction, frontal stiffness matching and passenger compartment strength. The development of a new deformable barrier face and revised performance criteria for the full width test to assess structural interaction are described. Analysis of the load cell wall data collected in EuroNCAP tests, to address the frontal stiffness problem, is reported. Performance criteria are suggested and future work necessary to help set performance limits outlined. Initial work to investigate the repeatability of the passenger compartment strength test and possible performance criteria are described. This research is being carried out in co-operation with the European Enhanced Vehicle-safety Committee (EEVC) and the International Harmonisation of Research Activities (IHRA) Working Groups, and is funded by the UK Department for Transport (DfT).

INTRODUCTION

Compatibility is now recognised as the next major step forward for improving car occupant safety and reducing road casualties. Since 1995, research carried out by TRL on behalf of the Department for Transport (DfT) has changed focus from frontal impact to compatibility. This ongoing work is being used to support the European Enhanced Vehicle-safety Committee (EEVC) and the International Harmonisation of Research Activities (IHRA) compatibility working groups.

Initially this research was aimed at gaining an understanding of compatibility and the factors that affect it. Having achieved this, more recent research has focussed on developing test procedures able to measure the most important characteristics that influence compatibility. Prior to this research, the conventional wisdom was that compatibility problems were limited to crashes between cars of different masses, where mass ratio had the dominant influence. Now it is clear that it is the effect that mass has on frontal stiffness that is primarily responsible for this effect. Furthermore, the importance of good structural interaction between impacting cars has been highlighted (1). This aspect of compatibility plays a part in virtually every road crash. Without good structural interaction, the energy absorbing capability of the frontal structure is compromised, leading to compartment intrusion in severe accidents. Once good structural interaction has been achieved, frontal stiffness matching between vehicles, combined with strong passenger compartments, should ensure that the impact energy is absorbed with minimal passenger compartment intrusion. Beyond this, there is scope for better optimisation of the car's deceleration pulse to minimise restraint induced deceleration injuries. With good compatibility, cars should perform in a more predictable manner over a range of impact configurations, enabling the meaningful development of advanced restraint systems.

For the year 2000, Great Britain's national accident statistics show that two-thirds of the road accident casualties were in cars or light goods vehicles (2). Occupants of these vehicles accounted for about half of the fatalities and the seriously injured, which is typical for recent years. Using values calculated by the DfT for preventing a road accident casualty, the cost to society of these casualties was about £6.3 billion in 2000. Although the improved structural interaction aspects of compatibility are relevant for virtually all car frontal impacts, the main benefits from stiffness matching are expected in car impacts with another vehicle. The GB national data show that over sixty percent of fatal and seriously injured car occupant casualties in 2000 were in frontal impacts. Approximately two-thirds of these occurred in an impact with at least one other vehicle, the type of accident in which improved compatibility should offer most benefit (Table 1).

Table 1.
Distribution of car occupant casualties by first point of impact for Great Britain in the year 2000

First point of impact	Fatalities		Seriously injured	
	No	(%)	No	(%)
Front	1002	(60)	11931	(66)
Side	560	(34)	4123	(23)
Rear	65	(4)	1527	(8)
Other	38	(2)	473	(3)
Total	**1665**	**(100)**	**18054**	**(100)**

It is expected that improved vehicle compatibility will result in far better occupant compartment integrity in frontal impact accidents but precise assumptions about how a compatible car will perform are very difficult to make. A benefit analysis has been performed for GB, which assumed that improved vehicle compatibility would either, pessimistically, eliminate injuries related to contact with intruded parts of the vehicle interior, or optimistically, eliminate injuries related to contact with the vehicle interior whether it had intruded or not. It was then assumed that removal of these injuries from the existing accident data would quantify the benefits for the applicable occupant population. With the additional assumption that compartment integrity would be maintained for all impact severities, it was predicted that improved compatibility could save between 37 and 55 percent of car occupant fatalities in frontal impacts. This prediction can be regarded as an upper estimate as it unlikely that compartment integrity could be maintained for high speed impacts. Repeating the analysis using the assumption that compartment integrity would be maintained for impact severities up to 56 km/h Equivalent Test Speed, predicted that between 14 and 26 percent of fatalities would be saved. It is expected that the actual benefit lies somewhere between these predictions.

This paper summarises the current frontal impact compatibility problems and describes the current development status of three test procedures to address the fundamental issues, namely, structural interaction, frontal stiffness matching and compartment strength.

CURRENT COMPATIBILITY PROBLEMS AND PROPOSED TEST PROCEDURES

Structural Interaction

In rigid wall crash tests, the wall controls the way the impact deformation is distributed across the car's front, irrespective of the car's stiffness distribution, so ensuring good structural interaction. Cars designed with limited numbers of frontal load paths that have few interconnections can obtain good results in these tests. Unfortunately, when such cars impact each other the chances of their stiff structures interacting is very limited. This reduces the chance that the impact energy can be efficiently absorbed in the frontal structure in the designed manner. In severe accidents this leads to excessive compartment intrusion and subsequent occupant injury. This poor interaction can manifest itself as the lateral fork effect, where the stiff members of one vehicle penetrate the soft areas of the other vehicle, due to lateral misalignment, or the over-riding of one car's structure by that of the other. With no control over the height of car structures, geometrical mismatches can give rise to over-riding from static misalignment. Even when structures are aligned statically, dynamic over-riding may occur.

An example of the static misalignment problem was seen in a collision between a BMW 3 series and a VW Sharan. The higher stiff structure of the Sharan overrode the BMW lower rails leaving them virtually undeformed. It directly loaded the less stiff area of the BMW and subsequently pushed the engine onto the firewall (Figure 1). This prevented the BMW absorbing its share of the impact energy efficiently and probably resulted in an undesirable 'back loaded' compartment deceleration pulse shape (3), i.e. a low deceleration at the start of the impact leading to a high deceleration at the end of the impact, as the engine loaded the firewall.

The sensitivity of structural interaction with current cars has been demonstrated previously (3). A 100 mm variation in ride height, in an impact between two identical cars, resulted in significant over-riding of the raised car over the lowered one. The energy absorption capability of both cars was compromised, as the structures were not loaded in the intended manner. This resulted in greater intrusion for the lowered car at facia level and in the raised car at footwell level. Subsequent EUCAR simulation modelling indicated that over-riding can occur with a height difference of only 25 mm, with identical cars (4). Even where structures are aligned vertically, dynamic pitch or bending of the structure during the impact can lead to misalignment.

Figure 1. Comparison of damage to BMW (top) to Sharan (bottom) showing that Sharan has overridden BMW.

Detailed accident case studies performed using the UK CCIS database found that structural interaction is a major problem, with less than 2 percent of the 162 car to car frontal impact cases examined showing good interaction.

In order to achieve good interaction, it is important that the structures of each car meet something substantial on the other car to react against. Current views are that this is best achieved by utilising multiple load paths, with good links between them. These links may take the form of frontal inter-connections or of shear connections set back from the front. Such structures should provide a more homogeneous front against which the other car's structure can react. In addition to the provision of a homogeneous front, it is important that there is adequate vertical alignment to ensure, for example, that a low sports car could interact with the front of a high off-road vehicle.

The Offset Deformable Frontal Impact test was intended to encourage manufacturers to increase the number of load paths and links between them. Unfortunately, so far, few manufacturers have taken advantage of the weight saving opportunities of this approach. Most have simply increased the stiffness of the car's main rails. However, for load spreading, all cars now have substantial crossbeams between the main rails but few other frontal connections have been improved. No cars currently have effective lateral connections, at the bonnet latch platform level, and few have any significant vertical connections between the lower load path and any upper load path.

In summary, these aspects of compatibility are general to all frontal impacts, not just car to car impacts. Achieving good interaction will allow a car to perform more predictably in accidents, in terms of energy absorption and compartment deceleration. Apart from the resulting reduction in intrusion this would help advanced restraint systems to perform correctly and predictably.

A Full Width Test for Structural Interaction has been proposed that uses a load cell wall (LCW) to assess and control the car's frontal stiffness distribution. The logic behind this is that cars with more homogeneous fronts should offer greater potential for good structural interaction. However, there are some issues that generate problems when a rigid faced load cell wall is used:

- The parts of the car that first impact the wall are decelerated instantaneously giving rise to large inertial forces. Such forces are not present in impacts with deforming structures, such as other cars.
- Similarly, when the engine impacts the wall, it is brought to rest very rapidly generating high inertial forces. In a car to car impact, the engine can rotate or move slightly out of the way of the other car's engine, so reducing its deceleration.
- Localised stiff structures can form preferential load paths to the wall and reduce the loading from adjacent structures which are slightly set back. This does not occur in impacts with other cars.
- No relative shear is generated in the front structure to exercise any shear connections between load paths.

In order to overcome these problems, a deformable barrier face is fitted to the front of the load cell wall. As the test is also intended to function as a high deceleration test for frontal impact, care has been taken to ensure that the overall car deceleration has not been significantly affected by the addition of the deformable face.

Frontal Stiffness

All current frontal impact crash tests place direct or indirect controls on energy absorption and deceleration of the car. If there is inadequate energy absorption in the frontal structure intrusion occurs which, at some level, will be detected by the instrumented dummies. Similarly, the dummies are sensitive to the car's deceleration, which is detected through such things as chest loading from the seat belt. However, there are currently no requirements controlling the frontal stiffness of the car. Indeed, the tests encourage heavier cars to be stiff, in comparison with lighter cars. As all the tests place a limit on the car's deceleration, through control of dummy loading, all cars tend to have similar stopping distances in the tests. The dummy's experience of deceleration is totally independent of the mass of the car it is travelling in. Data from EuroNCAP tests show that most cars, irrespective of size, have an overall ride-down distance of 1200 (+/- 200) mm (Figure 2). This includes the depth of the deformable barrier face of 540 mm. As most manufacturers aim to limit the length of the front structure, for a variety of reasons, crush depths tend to be kept to the minimum.

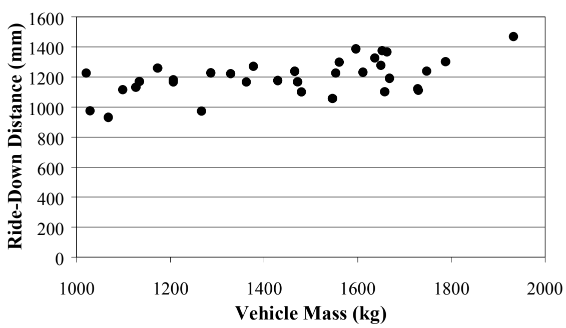

Figure 2. Ride-down distances recorded from EuroNCAP tests showing little variation with increasing mass. Note: Ride-down includes barrier depth of 540 mm.

With the energy absorbed being the integral of force against distance, the only way to maintain the same crush depth, whilst at the same time absorbing the car's kinetic energy, is for the frontal stiffness to increase with vehicle mass. This means that, even without other influences, current frontal crash tests lead to a stiffness incompatibility between cars of different mass.

Detailed accident case studies were performed using the UK CCIS database to quantify the size of frontal stiffness / compartment strength incompatibility problem. This was achieved by identifying cases where there was a significant intrusion difference between the colliding cars from the 162 car to car frontal impact cases examined. There were 78 cases where at least one of the vehicles had intruded and therefore it was possible to identify an intrusion difference. A significant intrusion difference was identified in 68 percent of these cases indicating that stiffness / compartment strength incompatibility problem is large. However, it should be noted that the extent to which poor structural interaction contributed to this problem is unknown.

In order to overcome this aspect of compatibility, it is necessary to control frontal stiffness by limiting the force imposed by a car on its opponent, in an impact. This may be less of a problem than it might at first appear. Data from EuroNCAP tests is indicating that the stiffness of some small cars has increased and becoming more in line with that of larger cars.

In setting a force limit requirement for cars, there are a number of factors to be considered:

- Whatever the force level is set to be, it will be necessary for the passenger compartments of all cars to be strong enough to resist this force without suffering significant intrusion.
- If the force level is set to be low, heavy cars will have to increase their available crush depth and may require longer front structures.
- If the force level is set to be high, light cars will have to become stiffer and the requirements for passenger compartment strength will also be high.
- A limit on how high the force level can safely be set will come from the potentially increased risk of deceleration induced injuries from the restraint system. A worst case situation would be where a low mass car had a full width frontal impact with a high mass car and the occupants were frail or elderly. For these occupants, the velocity change and deceleration of their cars will be high and there will be a limit to the ability of even advanced restraint systems to provide an adequate ride down.
- With a high force limit, the need to understand the influence of deceleration pulse shape, in combination with advanced restraints, will become more urgent.

A 64 km/h Offset Deformable Barrier (ODB) test for frontal stiffness has been proposed that uses a LCW to assess and control the force generated by the car. This requirement could simply be added to the current EuroNCAP type test. As previously reported (5), the load measured is a combination of the force coming from the deceleration of the passenger compartment (structural component) and the force coming from the deceleration of the mainly rigid masses ahead of the firewall (mechanical component), a large proportion of which is due to the engine and gearbox. In setting a limit for this force, it is necessary to consider the extent to which the engine force needs to be taken into account. In a car to car impact some of the engine load directly acts on the engine of the other car and has little effect on the structure. The remaining load does act on the structure, either directly or indirectly. The deformable face can attenuate the force to decelerate the engine and this may allow the maximum total force measured by the load cell wall to be used.

There may also be a need to set a minimum force level for the car front, so producing a range for the acceptable forces. This would prevent the design of small cars with excessively soft fronts, where the deceleration pulse might have to increase rapidly, when the front structure bottoms out on the strong passenger compartment. Such deceleration pulses are known to be injurious. It is unlikely that a minimum force requirement would come into play for larger cars, as there is no indication that any manufacturer has an interest in producing a long soft fronted car.

Compartment Strength

The frontal stiffness test effectively sets a limit for the force that one car can impose on its opponent. However, it gives no guarantee that the passenger compartment can sustain the load imposed by another car. For example, where a car, which generated a force well below the limit in the frontal stiffness test, impacted one which generated a force near to the limit, there could be no confidence that its passenger compartment would survive. Furthermore, any slight variation in the impact configuration might affect the force levels. For these reasons, it will be necessary to have a requirement for the strength of the passenger compartment, ensuring that it can resist forces greater than those used to control frontal stiffness.

It is clear that the strength of the passenger compartment is dependent upon the load paths used to transmit forces to it. In a frontal impact the most important load paths are the main rails, the upper rails, the engine subframe, via the road wheel to the sill and via the engine to the firewall. The upper rails and / or engine subframe may or may not be present. The way the loads are distributed between these load paths is dependent upon the car design, the impact configuration and the characteristics of the object hit. As the distribution of loads between the load paths varies, so the effective strength of the passenger compartment also varies. In order to ensure survival of the passenger compartment, cars should be designed to be tolerant of the distribution of the impact load. In principle this could be achieved by having a passenger compartment which is strong enough, irrespective of some variation in load path use, or by having a frontal structure that controls the way loads are distributed to the various load paths. The indications are that good structural interconnections control adjacent load paths to deform together and help to achieve this.

An 80 km/h ODB test to measure the compartment strength has been proposed that uses a LCW to assess and control the force generated by the car. It should be pointed out that there is no intention to require that cars provide a survivable performance for the occupants, at this severity. The test is simply designed to measure the strength of the passenger compartment.

If the passenger compartment becomes unstable in the impact, it will be necessary to ensure that the strength measured is prior to any major intrusion occurring. Once the passenger compartment becomes unstable, the measured load can be expected to reduce but it might again increase if subsequent structural blocking occurs. However, with conventional car designs this is unlikely.

CURRENT DEVELOPMENT STATUS OF TEST PROCEDURES AND ASSOCIATED PERFORMANCE CRITERIA

Full Width Deformable Barrier Test

This section describes the development of a new deformable barrier face, the modification of a current car to improve its structural interaction compatibility and the revised performance criteria for this test.

Development of a new deformable barrier face. Initial development work for this test was performed with a deformable face that consisted of 150 mm deep aluminium honeycomb element with a longitudinal crush strength of 0.34 MPa. A series of full width tests using this face were performed with current cars varying in size from small family to an off-road vehicle, using an impact velocity of 56 km/h. High resolution load cell wall measurements were recorded using a wall, which consisted of 128 load cells of size 125 mm by 125 mm arranged in a 16 by 8 matrix. These results have been reported previously (6).

Unfortunately, the results of some of these tests have shown that localised stiff structures on the car can form preferential load paths, which dramatically reduced loading from adjacent structures leading to an incorrect assessment of the stiffness homogeneity of the car. An example of this effect was seen with a family sized car, which has several such structures, namely a towing eye and radiator mount brackets located on the engine subframe (Figure 3).

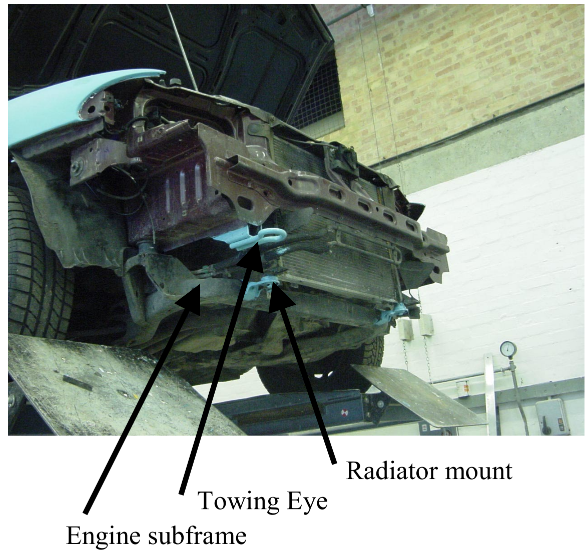

Figure 3. View of family sized car structure showing towing eye and radiator mount bracket protruding structures.

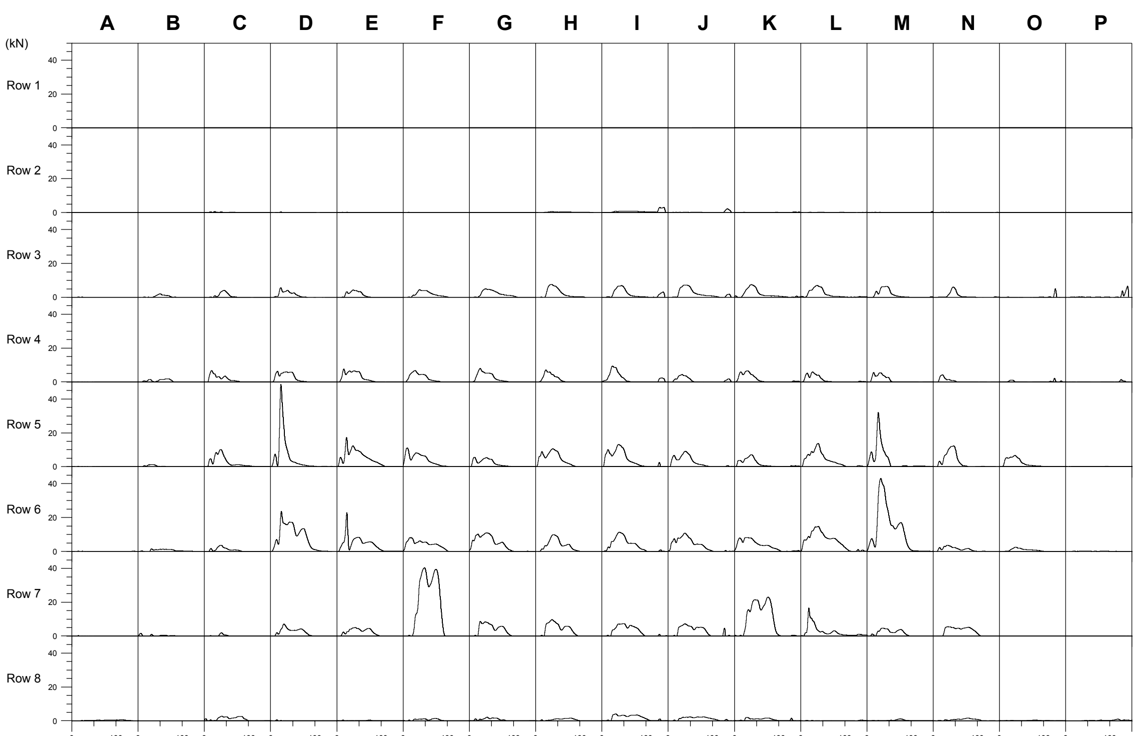

Figure 4. Load (scale 0 –50kN) / time (scale 0-150ms) curves for complete load cell wall for 0.34 MPa barrier face. Row 7 shows loading from engine subframe crossbeam with substantially higher loads recorded on cells in columns F and K caused by preferential loading of these cells by radiator mount brackets.

Examination of the deformed car and barrier face showed that the front crossbeam of the engine subframe applied load to row 7 of the load cell wall (LCW) with over 50 percent of this load being applied to the two cells in columns F and K (Figure 4). This was caused by the radiator mount brackets penetrating the deformable barrier face to make direct contact with the LCW to form preferential load paths. These unloaded the adjacent crossbeam structure. Unfortunately, this load distribution was not representative of the stiffness homogeneity of the crossbeam structure.

In order to resolve this problem the barrier face was redesigned. Following several iterations, the new barrier face design has two layers, each 150 mm deep. The front layer consists of a 0.34 MPa crush strength honeycomb element, the same as the original face, and the rear layer consists of a 1.71 MPa honeycomb element. The rear layer is segmented into individual blocks the same size as the load cells so that each block can be aligned with a load cell behind the barrier face. The reason for segmenting this layer was to reduce its shear strength to prevent the bridging of recessed load cells. Bridging can cause a redistribution of the load measured on the LCW leading to an incorrect representation of the stiffness homogeneity of the car being assessed.

It was proposed to repeat the test with the family sized car that showed the preferential load path problem using this new barrier face. However, due to technical difficulties in the manufacture of this face, which were later overcome, a face with a rear layer depth of 85 mm instead of 150 mm was used to repeat the test. The LCW results from this test are shown in Figure 5. Comparison of the LCW results from this test with those from the original single layer face (Figure 4) show that the revised face gives a much more even force distribution along the row which was loaded by the engine subframe crossbeam (row 7). This load distribution is a much better representation of the stiffness homogeneity of the crossbeam structure. Examination of the barrier face following the test showed that the radiator mount brackets had penetrated the stiffer rear layer of the face but had not made direct contact with the LCW, which allowed the rest of the crossbeam to load the wall.

One of the requirements of the barrier face is that, compared to a rigid wall test, it should have a

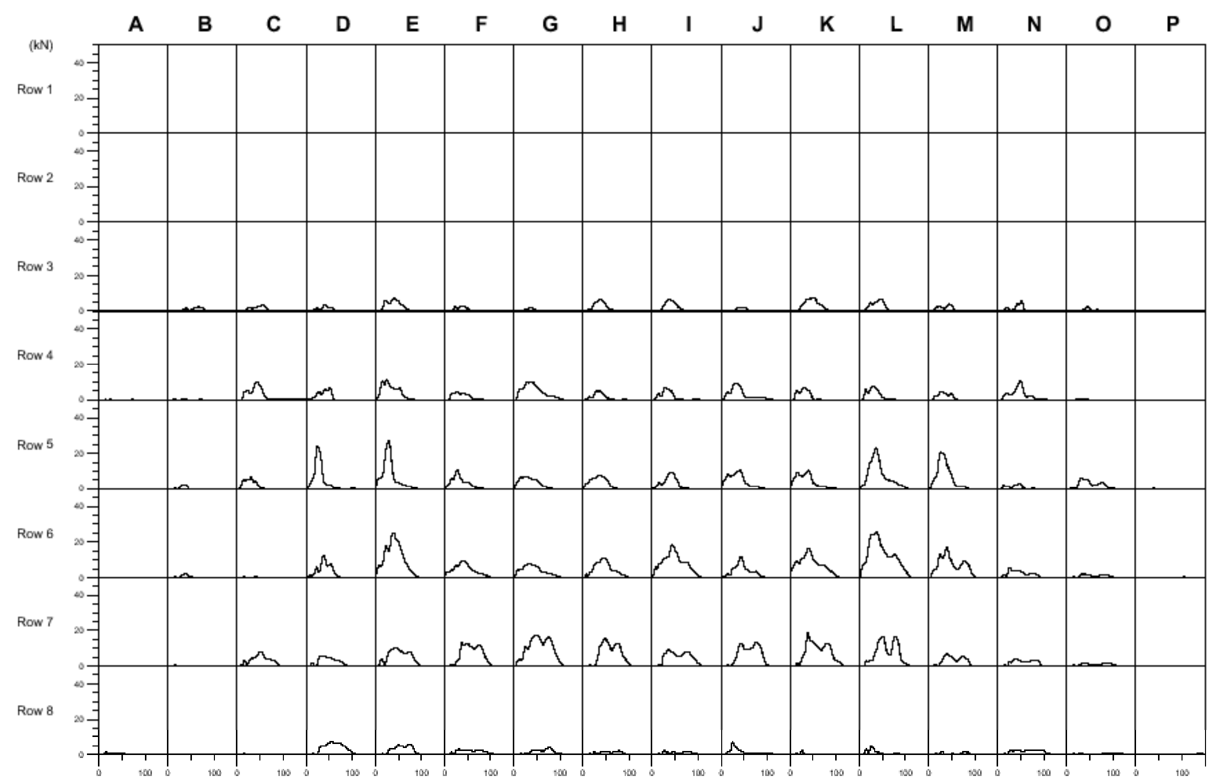

Figure 5. Load (scale 0–50kN) / time (scale 0-150ms) curves for complete load cell wall with double layer barrier face with 85 mm deep segmented rear layer showing even distribution of load on row 7 from engine subframe crossbeam.

minimal effect on the occupant compartment deceleration pulse so that the test could be used as a high deceleration frontal impact test similar to US FMVSS 208. A comparison of the compartment deceleration pulses from equivalent rigid wall and deformable barrier tests shows that the new face meets this requirement (Figure 6).

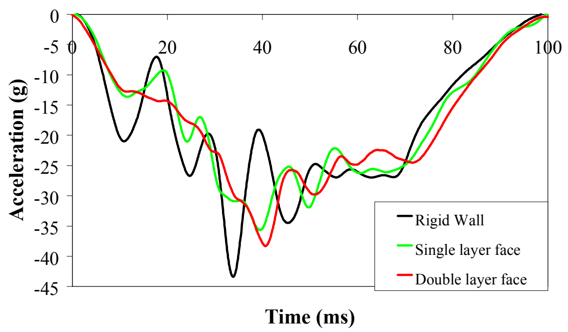

Figure 6. Comparison of compartment decelerations from rigid wall and deformable barrier tests showing minimal effect of deformable face. Note: single layer face (150mm, 0.34 MPa), and double layer face (1st layer 150mm 0.34 MPa, 2nd layer 85 mm 1.71 MPa, segmented).

In summary, a new barrier face was developed which overcame the preferential load path problem while still meeting the requirements of the original face. These were, compared to a rigid wall test, a) to attenuate the initial high decelerations at the front of the car and reduce the magnitude of the engine loading to make the test more representative of a vehicle to vehicle impact and b) to minimise the effect of the face on the compartment deceleration pulse for the reason mentioned above.

Modification of a car to improve its compatibility

A current European mid-sized car was modified to improve its compatibility and hence demonstrate the principles of how a car's compatibility performance, in particular its structural interaction potential, can be improved. The approach taken was to identify a suitable car to be modified, that not only exhibited poor structural interaction in a car to car crash test, but also would allow for additional load paths and vertical and lateral connections to be added to its base structure to improve its compatibility. A repeat car to car crash test with modified cars would then be performed and compared to the test with unmodified cars to demonstrate the improved crash performance. The car chosen for modification had lower rails which extended significantly further forward than the other load paths (Figure 7). This type of single level load path design is much more susceptible to under / override problems than a multi level one because of its smaller frontal interaction area.

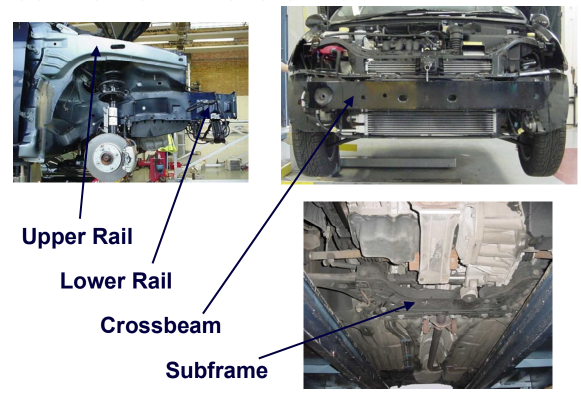

Figure 7. Side, front and bottom view of mid sized car structure showing forward extent of lower rails compared to other load paths.

The modifications made were the addition of a lower load path and additional frontal vertical and horizontal connections to provide a structure with a more homogeneous stiffness distribution to improve structural interaction. The additional lower load path was made by attaching an extension to the engine subframe. The extension consisted of two arms with a deep front crossbeam horizontal connection. It had a large thin walled box section design to maximise the proportion of energy absorbed in axial crush compared to bending (Figure 8).

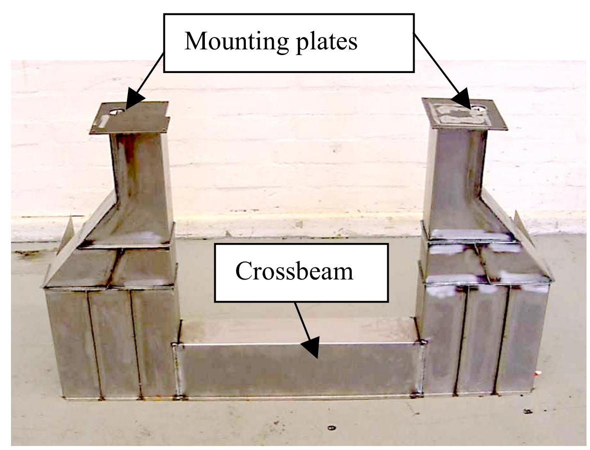

Figure 8. Engine subframe extension consisting of two arms and front crossbeam. Extension was attached to engine subframe via mounting plates.

The subframe extension was attached to the lower rails by vertical shear connections, which were formed from metal plate with additional ribs to increase their shear capacity (Figure 9). The modifications added a total mass of 16 kg to the car. The mounting plates accounted for 6 kg of this.

Initially, it was also proposed to include additional shear connections between the lower and upper rails. However, this was not done because supporting finite element analysis work showed that this would most likely increase the load through the upper rails, which could not be supported by the door aperture.

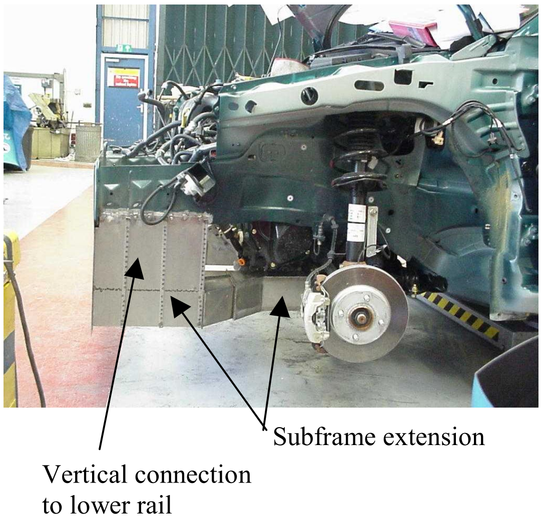

Figure 9. Modified car showing subframe extension and vertical shear connection to lower rail.

The results from a car to car impact test between unmodified cars were compared with those from an identical test with modified cars. The test configuration was 50 percent overlap with a 112 km/h closing speed. Also one car was raised to give a 60 mm ride height difference between the cars to promote any under / override that was likely to occur. The deformation of the lower car from each test shows that the occupant compartment deformation was substantially less for the modified car especially above waist rail level, indicating that less under / override has occurred with the modified cars (Figure 10). For the raised cars the modified car had less compartment deformation than the unmodified one but the difference was not as great as for the lower cars (Figure 11). Furthermore, the modified car had had less floorpan and sill deformation even though it had an additional load path at this level.

Unfortunately, the structural interaction performance for the modified cars was not improved as much as expected because the vertical shear connections between the engine subframe extension and the lower rails failed on the impacted side of the car for both the lower and raised cars. This was caused by spot weld failure.

In summary the crash performance of the modified cars was better than the unmodified ones because of the improved structural interaction and increased energy absorption of the frontal structure given by the additional load path and frontal connections.

Unmodified Car

Modified Car

Figure 10. Comparison of lower cars from car to car impact tests showing reduced occupant deformation of modified car.

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Unmodified Car

Modified Car

Figure 11. Comparison of raised cars from car to car impact tests showing the reduced sill deformation between the B and C pillars for the modified car.

Development of revised performance criteria. Full width deformable barrier tests using the new face were conducted with an unmodified and modified car to check that the test and assessment technique could correctly distinguish the improved stiffness homogeneity of the modified car given by its additional load path. Unfortunately, it was found that although a subjective assessment of the load cell wall results correctly ranked the modified car as having a better homogeneity than the unmodified car the Coefficient of Variance assessment technique reported previously (6) incorrectly ranked the cars. Because of this failure a new technique to objectively assess the force homogeneity was developed.

The revised homogeneity criterion is based on the difference between peak cell loads and an ideal or target load level over a specified assessment area or footprint. The calculation of the homogeneity consists of the following steps, which are described, in more detail below:

- LCW data smoothing.
- Determination of peak cell loads.
- Definition of assessment area.
- Calculation of target load level.
- Calculation of homogeneity criterion.

A small variation in the test configuration, such as the alignment of the car with the barrier, may change the number of load cells that a main structure, such as a lower rail, loads. This can alter the homogeneity assessment causing problems with the repeatability and reproducibility of the test. To overcome this problem the entire LCW data set is smoothed. The smoothing process involves averaging the output of four adjacent load cells and allocating this value to the centre point of these cells in a stepwise manner for each of the load cells at each time step. Following this, the maximum load recorded on each cell of the smoothed data set is determined.

The methodology to determine the assessment area is still under development. To ensure good structural interaction, this area should be defined to include the main structure of the vehicle and to ensure that there is adequate geometrical overlap, both vertically and horizontally, for all vehicles. Currently, to define the area vertically, a methodology based on defining a minimum vertical extent and controlling the average height of force (AHOF) is being investigated.

A simple way to determine the target load level to achieve homogeneity within the assessment area would be to sum the peak cell forces within the area and divide by the number of cells in the area. However, to encourage all loads applied to the wall to be applied within the assessment area the target load was defined as the sum of all the smoothed data set peak cell forces (whether inside or outside the area) divided by the number of load cells in the assessment area.

The homogeneity criterion is based on the square of the difference between the peak smoothed data set cell load levels and the target load level. The reason for this was to additionally penalise loads that varied significantly from the target load level. The homogeneity is calculated for cells, rows and columns of the smoothed data set as defined in the equations below. The row and column measures are included to assess the force homogeneity between rows (vertically) and columns (horizontally), respectively. The reason for this was that although the cell assessment provides an indication of the global cell force homogeneity, it did not take into account the relative position of the cells. The overall homogeneity criterion is calculated by summing the individual cell, row and column assessments. However, if, in the future, it is determined that one assessment measure was more important than the others were, then weighting could be applied to bias the homogeneity criterion appropriately.

Cell homogeneity

$$V_c = \frac{\sum_{i=1}^{n_C} (L - f_i)^2}{n_c}$$

Row homogeneity

$$V_r = \frac{\sum_{j=1}^{n_r} \left[\frac{L.n_{cl} - \sum_{i=1}^{n_{cl}} f_{ij}}{n_{cl}} \right]^2}{n_r}$$

Column homogeneity

$$V_{cl} = \frac{\sum_{j=1}^{n_{cl}} \left[\frac{L.n_r - \sum_{i=1}^{n_r} f_{ij}}{n_r} \right]^2}{n_{cl}}$$

where:
L = Target load level.
f = Peak cell force.
n_c = Number of cells in the assessment area.
n_{cl} = number of columns in the assessment area.
n_r = number of rows in the assessment area.

This revised homogeneity assessment technique has been shown to correctly rank the unmodified and modified cars described previously (Figure 12). The assessment area was determined from a subjective examination of the LCW data. It is interesting to note that the modified car's additional load path results in a much improved row (vertical) homogeneity assessment.

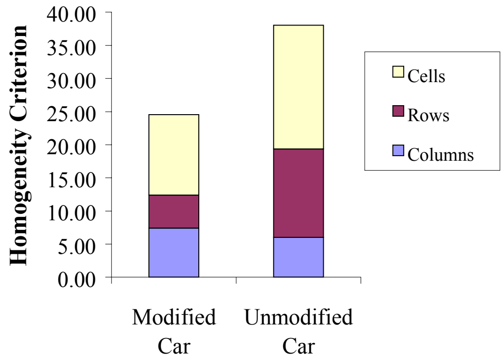

Figure 12. Homogeneity Criterion for unmodified and modified European mid sized car broken down into cell, row and column assessment.

Frontal Stiffness Test

The potential of controlling a car's stiffness by using the peak LCW force measured in a 64 km/h ODB test has been demonstrated and reported previously (6). A 50 percent overlap car to car test, with a closing speed of 112 km/h, was conducted between two small cars with a mass ratio of 1.01. Intrusion measurements showed that the car, which had recorded a lower peak load cell wall measurement (240 kN c.f. 310 kN) in the 64 km/h ODB test, suffered relatively more intrusion in the car to car test than in the ODB test.

As mentioned previously, the LCW force is a combination of the force coming from the deceleration of passenger compartment (compartment component) and the force coming from the deceleration of the mainly rigid masses ahead of the firewall (mechanical component), a large proportion of which is due to the engine and gearbox. For a typical car, the 'mechanical' component is relatively constant, as the engine and gearbox decelerate gradually, as the car deforms the barrier (Figure 13).

However, in a small number of cases, the magnitude of the mechanical force component increases significantly towards the end of the impact, which increases the peak LCW force recorded (Figure 14). This is caused by the engine 'bottoming out' the deformable barrier face and directly loading the wall. It would be more difficult for cars that exhibit this behaviour to comply with a LCW force maximum limit. However, it is not believed that this would be detrimental as, generally, these cars have little structure ahead of the engine, making them more aggressive. On the other hand, small cars could use this approach to help comply with a minimum force requirement. Further work is necessary to determine if this could be a significant problem.

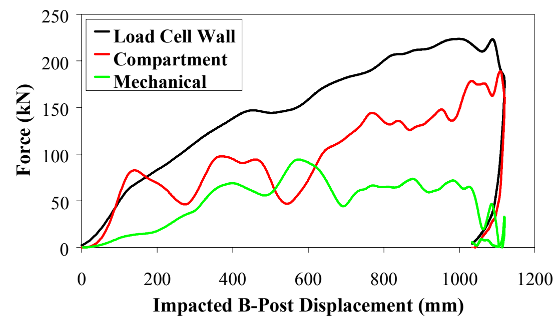

Figure 13. Load Cell Wall force showing passenger compartment and mechanical components for a typical car in a 64 km/h ODB impact.

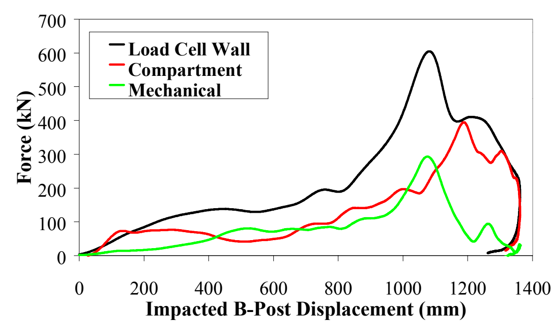

Figure 14. LCW force measured for a 64 km/h ODB test of large family car showing large mechanical force component towards end of crash.

As part of the continuing development of this test procedure, LCW peak force measurements have been taken for many recent EuroNCAP tests (Figure 15). Examination of the data shows that the peak forces lie in the range from 200 to 500 kN. From this information a first estimate for a maximum force limit could be 400 kN and for a minimum 300 kN. To determine whether these suggested values are appropriate and practicable much further work is necessary to address the issues mentioned previously. These are passenger compartment strength, deceleration pulse and the need to increase the crush depth in heavier cars.

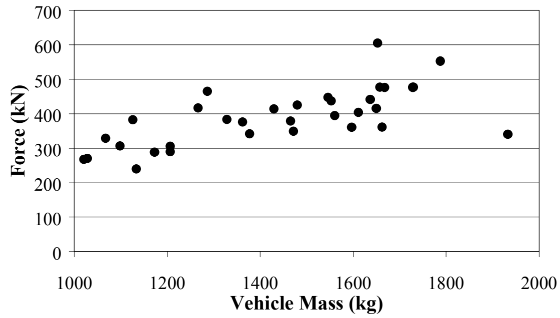

Figure 15. Peak Load Cell Wall measurement for EuroNCAP tests.

Compartment Strength Test

Typically in an 80 km/h ODB test, towards the end of the impact the engine has 'bottomed out' the deformable barrier face and stopped decelerating so that the LCW force consists mainly of the passenger compartment force component (Figure 16). The LCW force at this point is termed the 'end of crash force,' a phrase first used by Renault (7). This force represents the load imposed on the compartment and hence can be used as an indication of a minimum load that the compartment can withstand for this loading configuration. From the limited number of tests performed, it appears that the time at which the difference of the compartment deceleration and average engine deceleration records a maximum can be used to determine the time at which the 'end of crash force' should be measured. It is possible that the end of crash force requirement may be achieved with just one load path, for example via the road wheel to the sill. To ensure this does not occur, intrusion limits may also be necessary, in particular at waist rail level. Further work is necessary to address this issue.

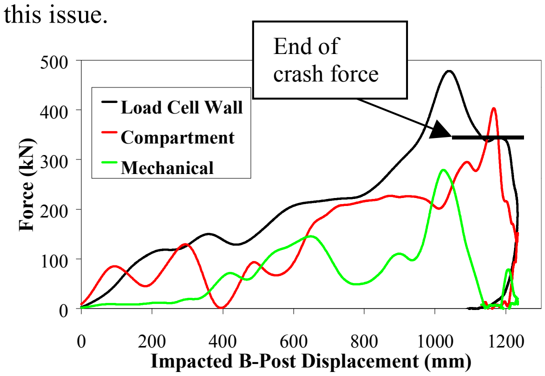

Figure 16. LCW force showing compartment and mechanical components for 80 km/h ODB test.

Some concern has been expressed about the possible repeatability of this test especially if the passenger compartment becomes unstable (4). Two similar tests have been performed for a super mini size car with an impact speed of 80 km/h. These show good repeatability for the LCW force (Figure 17) and the car's deformation (Figure 18) even though the load path through the door beam has become unstable.

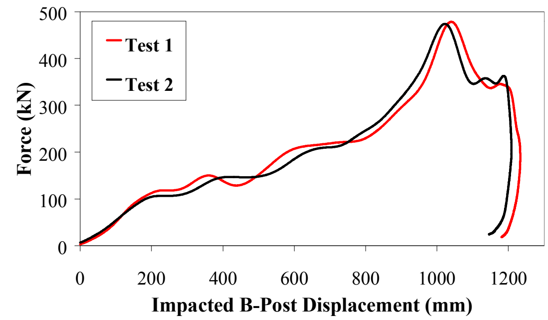

Figure 17. Load Cell Wall force for two 80 km/h ODB tests with a super mini size car showing good repeatability.

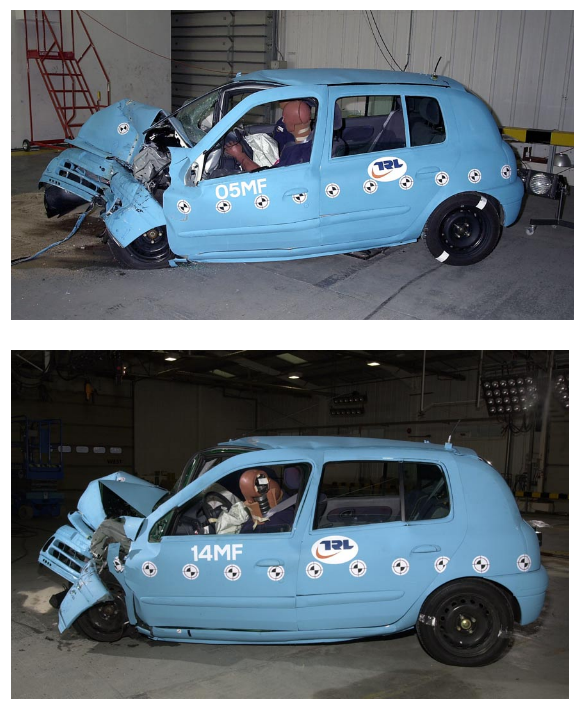

Figure 18. Deformation for two 80 km/h ODB tests with a super mini size car showing good repeatability.

The compartment strength measured in this test will be dependent on the load paths used. One possible concern, which requires further investigation, is that the wheel to sill load path is used more in this test configuration than it would be in accidents.

If a maximum force level of 400 kN is set for the frontal stiffness test, a suggested minimum limit for the end of crash force to control the compartment strength may need to be somewhat greater, say 450 kN. However, it may be possible to set the limit lower and still allow a sufficient safety margin. In a car to car impact some of the engine load acts directly on the engine of the other car and does not act on the passenger compartment. It is possible that not all of the engine component of the LCW force measured in the frontal stiffness test acts on the passenger compartment in a car to car collision, so this may allow a sufficient safety margin to set the limit lower. One advantage of a lower limit would be to minimise the risk of car designs where the deceleration pulse might have to increase rapidly when the front structure bottomed out on the strong passenger compartment. Further work is required to check that the suggested value of 450 kN is appropriate and practical.

CONCLUSIONS

The first requirement for frontal impact compatibility is to ensure good structural interaction. It helps to address problems seen in all frontal impacts and without it any control of stiffness would have limited effect. With good structural interaction, it will then be possible to control frontal stiffness and passenger compartment strength. An inevitable consequence of these actions to reduce passenger compartment intrusion is that car deceleration will increase along with associated injuries, unless they are mitigated by improved restraint systems. Although any increase in injuries from deceleration is likely to be small compared with the decrease due to improved passenger compartment survival, there is going to be a growing need to understand the importance of and potentially control the shape of the deceleration pulse.

To address these issues and improve compatibility three test procedures are under development. It should be noted that two of these are modifications of current tests. The tests are:

- ♦ A full width test at 56 km/h (the current US NCAP test) with a deformable barrier face and high resolution load cell wall (LCW) to assess and control structural interaction. This will be achieved by controlling the force distribution measured on the LCW, to encourage the development of structures that behave in a more homogeneous manner.
- ♦ A 64 km/h Offset Deformable Barrier (ODB) test (the current EuroNCAP frontal test) with a high resolution LCW. From the load cells, the car's frontal stiffness could be controlled by specifying that the peak force recorded should lie within a specified range. In the future, some control of the pulse shape could be used to manage the passenger compartment deceleration and restraint loading.
- ♦ An 80 km/h ODB test with a LCW to assess the strength of the passenger compartment. This test would not require instrumented dummies.

One advantage of this set of tests for frontal impact is that the full width test would generate a 'hard' deceleration pulse on the vehicle and restraint system, whereas the 64 km/h ODB test would generate a 'soft' pulse. This would ensure that restraint systems are better able to deal with both types of pulse. Another advantage is that, assuming the full width and 64 km/h ODB tests are specified for frontal impact world wide, only one additional test would be required for compatibility.

The current state of development of these test procedures has been reported, covering issues such as the development of a new deformable barrier face and a revised homogeneity assessment technique for the full width test. A car has been modified to demonstrate the principles of how a car's compatibility performance, in particular its structural interaction potential, can be improved. It has been shown that the full width test procedure with the new barrier face and revised assessment technique correctly ranks the better structural interaction of the modified car above that of the unmodified car. Some performance limits for the frontal stiffness and compartment strength tests have been tentatively suggested. However, further work is required to ensure that these suggestions are appropriate and practicable.

In addition, the benefit of improving compatibility for the UK has been estimated and shown to be substantial.

This is an evolving area and much further work is required to complete the development of these procedures to a level suitable for consumer and / or legislative use.

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